BNL–67629
August 15, 2000

Future Kaon Programs at BNL, FNAL [1]

S.H. Kettell

Brookhaven National Laboratory

Abstract. Future kaon decay programs at BNL and FNAL are discussed. The primary focus of these programs is the measurement of the golden modes, $K^\circ_L \to \pi^\circ \nu\overline{\nu}$ and $K^+ \to \pi^+ \nu\overline{\nu}$. The observation of $K^+ \to \pi^+ \nu\overline{\nu}$ by E787 at BNL is the first step in a series of measurements which will completely determine the unitarity triangle within the kaon system.

The next step after E787 in the measurement of B($K^+ \to \pi^+ \nu\overline{\nu}$) will be the E949 experiment at BNL that is currently under construction. This experiment, building on the experience of E787 and making use of the intense AGS proton beam, is scheduled to run in FY01–03 and to observe $\mathcal{O}(10)$ SM events with a small and well-understood background. The proposed CKM experiment at FNAL would take the next step, using a decay-in-flight technique and a 22 GeV/c RF-separated kaon beam from the Main Injector, to observe $\mathcal{O}(100)$ SM events.

At the same time, two concepts for the measurement of B($K^\circ_L \to \pi^\circ \nu\overline{\nu}$) have been developed. One of these, building on the experience of KTeV with a 'pencil' K_L beam, has been proposed at FNAL as KAMI. The other, with a measurement of the kaon momentum in a large angle K_L beam derived from a bunched proton beam, has been proposed at BNL as KOPIO.

INTRODUCTION

The decays $K^\circ_L \to \pi^\circ \nu\overline{\nu}$ and $K^+ \to \pi^+ \nu\overline{\nu}$ are two of the 'golden modes' for measuring CKM parameters. Measurement of the branching ratio B($K^+ \to \pi^+ \nu\overline{\nu}$) provides a clean and unambiguous determination of the CKM matrix element $|V_{td}|$, in particular of the quantity $|\lambda_t| \equiv |V^*_{ts} V_{td}|$. Measurement of the direct-CP-violating decay $K^\circ_L \to \pi^\circ \nu\overline{\nu}$ will cleanly determine the imaginary part of λ_t, $Im(\lambda_t)$.

The theoretical uncertainty in $K^+ \to \pi^+ \nu\overline{\nu}$ is quite small (∼7%) and even smaller in $K^\circ_L \to \pi^\circ \nu\overline{\nu}$ (∼2%), as the hadronic matrix element can be extracted from the $K \to \pi e \nu_e$ branching ratio. The $K \to \pi \nu\overline{\nu}$ branching ratios have been calculated to next-to-leading-log approximation [1], complete with isospin violation corrections [2] and two-loop-electroweak effects [3]. Fits based on the best current data

[1] To be published in the *Proceedings of the 7th Conference on the Intersections of Particle and Nuclear Physics; Quebec City, Canada, May 22-28, 2000*; Z. Parsa and W. Marciano, Eds.

for the CKM matrix elements give branching ratios of [4]

$$B(K^+ \to \pi^+ \nu\overline{\nu}\ ) = (8.2 \pm 3.2) \times 10^{-11} \tag{1}$$
$$B(K_L^\circ \to \pi^\circ \nu\overline{\nu}\ ) = (3.1 \pm 1.3) \times 10^{-11}.$$

These branching ratios are very small and, with two neutrinos in the final state, both of these experiments are challenging.

MEASUREMENT OF $|V_{td}|$ FROM $K^+ \to \pi^+ \nu\overline{\nu}$

The E787 experiment at BNL was designed to search for $K^+ \to \pi^+ \nu\overline{\nu}$ and reported the first observation of $K^+ \to \pi^+ \nu\overline{\nu}$ from analysis of the 1995 data set [5]. A new analysis of the 1995 data combined with the 1996 and 1997 data sets, has reduced the background levels by about a factor of three. A plot from the 1995–97 data set [6] of the range vs. energy of events passing all other $K^+ \to \pi^+ \nu\overline{\nu}$ criteria is shown in Figure 1. One event is observed in the signal

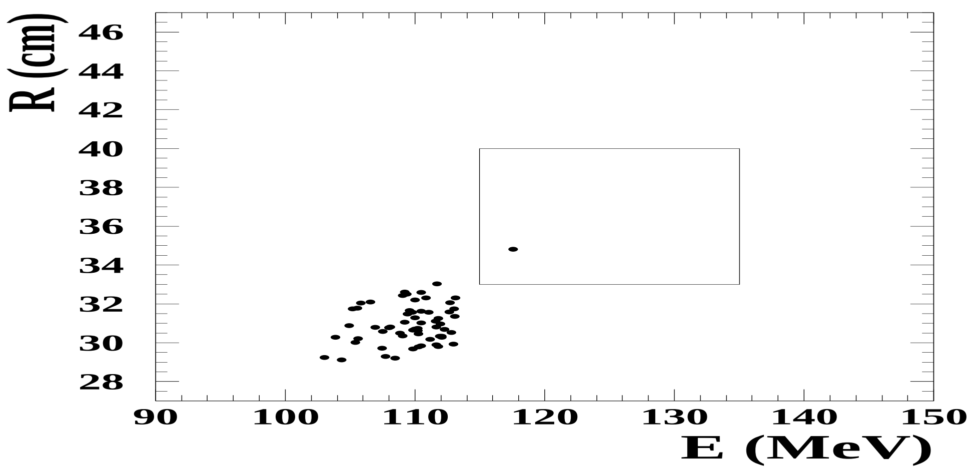

FIGURE 1. Range vs. Kinetic energy plot of the final sample. The events near $E = 108$ MeV are $K_{\pi 2}$ background. The box indicates the accepted region for $K^+ \to \pi^+ \nu\overline{\nu}$ events.

region with a measured background of 0.08 ± 0.02 events. The branching ratio is $\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = (1.5^{+3.4}_{-1.2}) \times 10^{-10}$. From this measurement, a limit on $|V_{td}|$ of $0.002 < |V_{td}\ | < 0.04$ can be derived, as well as the following limits on $\lambda_t \equiv V_{ts}^* V_{td}$: $|Im(\lambda_t)| < 1.22 \times 10^{-3}$, $-1.10 \times 10^{-3} < Re(\lambda_t) < 1.39 \times 10^{-3}$, and $1.07 \times 10^{-4} < |\lambda_t| < 1.39 \times 10^{-3}$. The E787 experiment has finished running and the final sensitivity, based on the complete 1995–98 data set, should reach the SM expectation for $K^+ \to \pi^+ \nu\overline{\nu}$.

E949 at BNL

A new experiment under construction, E949, is expected to run in 2001–03, symbiotically with RHIC. E949 will use the AGS proton beam, between fills of RHIC,

for approximately 20 hours/day. The E787 experiment has already demonstrated sufficient background rejection ($\sim$10% of the SM signal) for a very precise measurement of B($K^+ \to \pi^+ \nu\overline{\nu}$). Taking advantage of the very large AGS proton flux and the experience gained with the E787 detector, E949 with modest upgrades should observe $\mathcal{O}(10)$ SM events in a two year run. The background is small and well-understood.

CKM at FNAL

The CKM experiment was proposed in 1998 and has been pursuing R&D towards a full technical proposal in 2001 as E905 at FNAL. It would run simultaneously with the Tevatron collider using protons from the Main Injector that are not needed for the collider and extract them over a long spill ($\sim$1 sec). CKM plans to collect $\mathcal{O}(100)$ SM events with a background of $\mathcal{O}(10)$ events, starting sometime after 2005. This experiment will use an intense RF-separated 22 GeV/c kaon beam derived from the Main Injector. This novel K$^+$ decay-in-flight technique will obtain redundant kinematic measurements from independent momentum and velocity spectrometers. The kaon momentum will be measured in a Si spectrometer and the pion momentum in straw-tube drift chambers in the vacuum decay region. The velocities of the kaon and pion will be measured in RICH counters. Two large Pb-scintillator photon veto systems reduce backgrounds from $K^+ \to \pi^+ \pi^\circ$ decays and a muon veto system reduces background from $K^+ \to \mu^+ \nu_\mu$ decays.

MEASUREMENT OF $\boldsymbol{Im(V_{td})}$ FROM $\boldsymbol{K^\circ_L \to \pi^\circ \nu\overline{\nu}}$

Presently, the best limit on $K^\circ_L \to \pi^\circ \nu\overline{\nu}$ is derived in a model-independent way [7] from the E787 measurement of $K^+ \to \pi^+ \nu\overline{\nu}$:

$$\begin{aligned} B(K^\circ_L \to \pi^\circ \nu\overline{\nu}\ ) &< 4.4 \times B(K^+ \to \pi^+ \nu\overline{\nu}\ ) \\ &< 2.6 \times 10^{-9} \ \ (90\%\,\mathrm{CL}). \end{aligned} \tag{2}$$

The best direct limits come from the KTeV experiment at FNAL. KTeV used a narrow 'pencil' beam to define the transverse vertex position of $\pi^\circ \to \gamma\gamma$ decays in a one-day test run and observed one background event, probably from a neutron interaction. From this special run, a 90%-CL limit [8] of B($K^\circ_L \to \pi^\circ \nu\overline{\nu}$) $< 1.6 \times 10^{-6}$ was established. A better limit is obtained using the $\pi^\circ \to e^+e^-\gamma$ decay, which is inherently a factor of 80 less sensitive but has the significant advantage of a precise vertex location. Since the vertex location is known a larger, more intense kaon beam can be used; and the background levels are lower as the transverse momentum is known with better precision. In the full 1997 KTeV data set no events were seen, and at the 90% confidence level, $B(K^\circ_L \to \pi^\circ \nu\overline{\nu}\ ) < 5.9 \times 10^{-7}$ [9]. The P_T distribution of $\pi^\circ \to e^+e^-\gamma$ events passing all other cuts can be seen in Figure 2. The expected background was $0.12^{+0.05}_{-0.04}$, mainly from $\Lambda \to n\pi^\circ$ and $\Xi^\circ \to \Lambda\pi^\circ$.

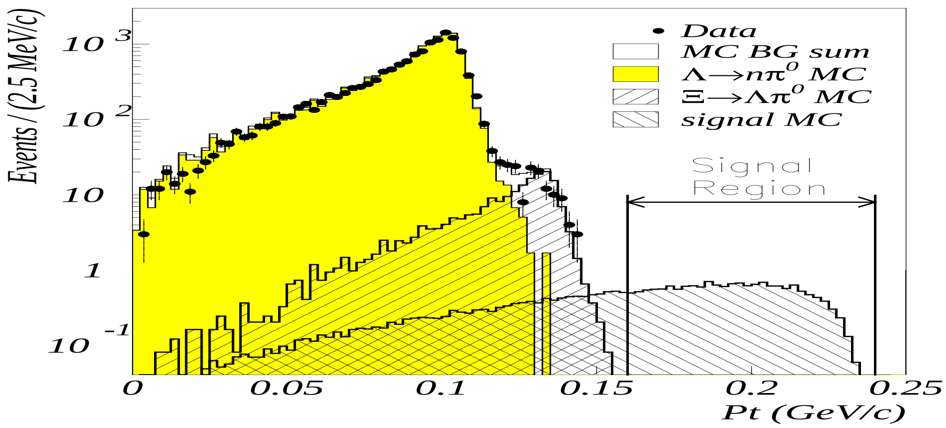

FIGURE 2. Final KTeV $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ ($\pi^\circ \to e^+e^-\gamma$) data sample collected during 1996–1997 after all cuts. No $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ events are seen above $P_T = 160$ MeV/c.

The next generation of $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ experiments, all using the $\pi^\circ \to \gamma\gamma$ decay mode, will start with E391a at KEK, which hopes to reach a sensitivity of $\sim 10^{-10}$, using a technique similar to KTeV. Although the reach of E391a is not sufficient to observe a signal at the standard model level, the experiment will be able to rule out large enhancements from new physics and learn more about how to do this difficult experiment. It is designed around a pencil K_L beam, a high-resolution crystal calorimeter, and very efficient photon veto systems. This experiment would eventually move to the JHF and aim for a sensitivity of $\mathcal{O}(10^{-14})$. Two other major efforts to observe and measure $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ are KAMI and KOPIO.

KAMI at FNAL

The KAMI collaboration submitted an expression of interest at FNAL for an experiement to measure B($K_L^\circ \to \pi^\circ \nu\overline{\nu}$). KAMI, like CKM, will make use of a slow extracted spill from the Main Injector, simultaneous with the operation of the Tevatron. KAMI plans to reuse the excellent KTeV CsI calorimeter, with a single high intensity pencil K_L beam directed through a hole in the middle. The decay volume upstream of the calorimeter will be surrounded by a hermetic, highly efficient array of photon veto detectors. An additional photon detector will catch photons escaping along the beam. The current design of the KAMI detector includes a fiber tracker to expand the number of secondary modes to be studied. KAMI expects to detect $\mathcal{O}(100)$ SM events in a couple of years of running with a background of $\sim$40% of the SM signal.

KOPIO at BNL

The KOPIO experiment at BNL has been given scientific approval and is currently undergoing funding review. It plans to run at the AGS after the completion of E949 and in the same mode, with ∼20 hours per day available between RHIC fills. KOPIO will reconstruct the kaon center of mass using a bunched proton beam and a very low momentum K_L beam. This technique allows for two independent criteria to reject background, photon veto and kinematics—allowing background levels to be directly measured from the data—and encourages further confidence in the signal by measuring the momentum spectrum of the decay. The necessary kaon flux will be obtained using the large available AGS proton current. The low-energy beam also substantially reduces backgrounds from neutrons and other sources. After three years of running, 65 standard-model events are expected with a S/B $\geq$ 2:1.

CONCLUSIONS

The unprecedented sensitivities of rare kaon decay experiments and the recent discovery of $K^+ \to \pi^+ \nu\overline{\nu}$ have opened doors to the measurement of the unitarity triangle completely within the kaon system. Significant progress in the determination of the fundamental CKM parameters will come from the generation of experiments that is now starting. These measurements can provide critical, unambiguous determination of the standard-model *CP* violation parameters. Comparison with the B-system will then over-constrain the triangle and test the SM explanation of *CP* violation:

- Comparison of the angle 2β from the ratio B($K_L^\circ \to \pi^\circ \nu\overline{\nu}$)/B($K^+ \to \pi^+ \nu\overline{\nu}$) and the CP asymmetry in the decay $B_d^\circ \to \psi K_S^\circ$ will provide one of the most important tests [7,10].
- Comparison of the magnitude $|V_{td}|$ from $K^+ \to \pi^+ \nu\overline{\nu}$ and the ratio of the mixing frequencies of B_s to B_d mesons will also provide an important test with small theoretical uncertainty [4].

ACKNOWLEDGMENTS

I wish to thank many people for discussions regarding this talk: particularly, Greg Bock, Laurie Littenberg, Ron Ray, Tony Barker, Bob Tschirhart, Robin Appel and Peter Cooper. This work was supported under U.S. Department of Energy contract #DE-AC02-98CH10886.

REFERENCES

1. Bucahalla G. and Buras A., *Nucl. Phys.* **B412**, 106 (1994).

2. Marciano W.J. and Parsa Z., *Phys. Rev.* **D53**, R1 (1996).
3. Bucahalla G. and Buras A., *Phys. Rev.* **D57**, 216 (1998).
4. Bucahalla G. and Buras A., *Nucl. Phys.* **B548**, 309 (1999).
5. Adler S., *et al.*, *Phys. Rev. Lett.* **79**, 2204 (1997).
6. Adler S., *et al.*, *Phys. Rev. Lett.* **84**, 3768 (2000).
7. Grossman Y., and Nir Y., *Phys. Lett.* **B398**, 163 (1997).
8. Adams J, *et al.*, *Phys. Lett.* **B447**, 240 (1999).
9. Alavi-Harati A, *et al.*, *Phys. Rev.* **D61**, 072006 (2000).
10. Bucahalla G. and Buras A., *Phys. Lett.* **B333**, 221 (1994); Bucahalla G. and Buras A., *Phys. Rev.* **D54**, 6782 (1996); Nir Y. and Worah M.P., *Phys. Lett.* **B423**, 319 (1998); Bergmann S. and Perez G., hep-ph/0007170.